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A PLAUSIBLE HYPOTHESIS FOR STRIATION FREEZING IN IONOSPHERIC PL--ETC(U)
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Ionospheric plasma cloud striation phenomena exhibit a persistence of kilometer scale size structures, i.e., a freezing. Beyond a certain point in time the striations drift in unison without further bifurcation. Recent theoretical and nonlinear numerical simulation studies using a one level, 2D plasma cloud model with cross field diffusion produced a U shaped curve for minimum striation scale size, i.e., a structure's stability against further

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20 ABSTRACT *(Continued)*

bifurcation, as a function of cloud to background Pedersen conductivity ratio (M). The minimum of the U (occurring for $M \approx 4$), with classical electron-ion collisions (diffusion), results in a minimum scale size $L_o \approx$ 10-20m. Even with M = 30, the results produced L_o = 50m, clearly are not the kilometer type scale sizes observed. On the other hand nonlinear numerical simulation studies using a two level, 2D model, without electron-ion collision induced diffusion, showed that high density cloud striations create, as time goes on, high density image striations beneath them in the background ionosphere. This effectively increases the Pedersen conductivity associated with the cloud striations. Knowing these two results and extrapolating the U shaped curve to higher M, yields $L_o \approx$ 500m for $M \approx 300$. Thus it is proposed that the second level (background ionosphere) effect of amplifying the conductivity in a striation, via image striations because the second level is compressible, could result in km size minimum scale sizes (non-bifurcation), as time goes on.

CONTENTS

A PLAUSIBLE HYPOTHESIS FOR STRIATION FREEZING IN IONOSPHERIC PLASMA CLOUDS

I. Introduction

Both barium cloud and nuclear cloud striation phenomena exhibit a persistence of kilometer scale-size structures, i.e., a freezing (J. Fedder, W. Chesnut, L. Wittwer, private communication, 1980). Beyond a certain point in time there is a tendency for the striations to drift in unison as long as they can be observed. It is almost as if a bulk electric field ($\underline{E}$) is acting on the entire cloud, causing an $\underline{E} \times \underline{B}$ motion. The basic question is: if the $\underline{E} \times \underline{B}$ gradient drift instability (Simon, 1963; Linson and Workman, 1970) is at work producing small structures through a series of bifurcations (Zabusky et al., 1973; Scannapieco et al., 1974; Scannapieco et al., 1976; Doles et al., 1976; Ossakow et al., 1977), then why do kilometer scale structures persist?

Two clues which may provide the answer are as follows. Recent theoretical and numerical simulation studies (modeling the plasma cloud and ionosphere as a single two dimensional layer perpendicular to the ambient geomagnetic field ($\underline{B}$), with cross-field diffusion due to electron-ion collisions) by McDonald et al. (1980) produced a "U" shaped curve for the minimum striation scale size (a structure's stability against further bifurcation) as a function of plasma cloud to background ionosphere integrated Pedersen conductivity ratio. The other clue is that two level (one for the plasma cloud ions and one for background ionospheric ions, two dimensional, without diffusion due to electron-ion collisions) plasma cloud striation numerical simulation studies (Scannapieco et al., 1976; S. Zalesak, private communication, 1980) show that high density cloud striations create high density image striations beneath them in the background ionosphere. This can effectively increase the integrated Pedersen conductivity associated with the plasma cloud striations. Thus, the answer to our question may be

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as follows. For barium cloud striations stir a little of the first clue with a little of the second clue. For nuclear cloud striations, the first clue in the very large Pedersen conductivity regime is sufficient. It should also be mentioned at this juncture that another hypothesis has been proposed for barium cloud striations by McDonald et al. (1980). In that model turbulent diffusivity (e.g., Bohm diffusion), some two orders of magnitude larger than classical diffusion, is invoked to account for the freezing phenomena. However, the cause of this turbulent diffusion was left as an unsolved problem.

Before proceeding to our model, let us outline the basics of the McDonald et al. (1980) and the Scannapieco et al. (1976) studies (for details the reader should consult these works). In the McDonald et al. (1980) work a one level, two dimensional (x,y) perpendicular to the ambient geomagnetic field, $\underline{B}$, ($\underline{B} = B\hat{z}$), striation model was used in which the equations were cast into the dimensionless form

$$\frac{\partial \Sigma'}{\partial t'} = - \nabla \cdot (\Sigma' \underline{V}') + R^{-1} \nabla^2 \Sigma' \tag{1}$$

$$\underline{V}' = - \nabla' \phi' \times \hat{\underline{z}} \tag{2}$$

$$\nabla' \cdot (\Sigma' \nabla' \phi') = \underline{v} \cdot \nabla' \Sigma' \tag{3}$$

$$R = V_o L_o / K \tag{4}$$

$$K = 2 \frac{\nu_e}{\Omega_e} \frac{c k_B T}{eB} \tag{5}$$

$$\nu_e \approx \nu_{ei} = (34 + 4.18 \log (T^3/n))\, n\, T^{-3/2} \tag{6}$$

In obtaining eqns. (1) - (3) from the dimensional equations the following were used

$$L_o = \text{scale length} \qquad \underline{x} = L_o \underline{x}'$$

$$V_o = cE_o/B \qquad \underline{V} = V_o \underline{V}'$$

$$t_o = L_o/V_o \qquad t = t_o t'$$

$$\Sigma = \Sigma_o \Sigma' \qquad \phi = L_o E_o \phi'$$

L_o is a measure of the cloud's gradient scale size, Σ_o is the ambient ionosphere integrated Pedersen conductivity, K is the cross field ($\underline{B}$) diffusion coefficient due to electron-ion collisions, n is plasma density, ν_{ei} is electron-ion collision frequency, Ω_e is the electron gyrofrequency, k_B is Boltzmann's constant, T is plasma temperature, e is electron charge, c the speed of light, V_o is the relative drift speed between the ambient plasma and the neutral atmosphere, ϕ is the induced electrostatic potential ($\underline{E} = \underline{E}_o - \nabla\phi$) and the ambient electric field was taken to be $\underline{E}_o = E_o \hat{\underline{y}}$. Equation (1) is derived from the electron continuity equation and eqn. (3) is derived from setting the divergence of the current equal to zero. It was noted that R was analogous to the Reynolds number for neutral flows. McDonald et al. (1980) noted that eqns. (1) - (3) revealed that the evolution of a plasma cloud was completely determined by initial cloud geometry, boundary conditions, and the value of R.

The answer to whether or not a given structure will bifurcate depends on whether R is greater than or smaller than some critical R value applicable to that structure. For sufficiently small R, diffusion will dominate and will smooth out all structures faster than they can be created. For sufficiently large R, diffusion will be negligible, allowing steepening and bifurcation to to take place. The marginally stable state (critical R) is achieved when the diffusion effect just balances the steepening process. If the critical R for a particular structure is known, one can use eqn. (4) to estimate the scale size of the marginally stable state, providing estimates are available for V_o and K,

$$L_o = KR/V_o \tag{7}$$

Utilizing the above, McDonald et al. (1980) investigated bifurcations which originate near the tips of striations. The procedure for estimating the critical R for a given initial condition on Σ was to carry out a set of simulations from eqns. (1) - (3) with assorted values of K. Initial conditions for the simulations were taken to be

$$\begin{aligned} \Sigma &= 1 + (M-1)\exp(-y^2/S^2) \qquad x < 0,\ S = 1\ \text{km} \\ &= 1 + (M-1)\exp(-(x^2+y^2)/S^2) \quad x \geq 0,\ S = 1\ \text{km} \end{aligned} \tag{8}$$

where M is the ratio of peak integrated Pedersen conductivity to ambient. For all cases B = 0.5 gauss, E_o = 5 mV/m, so that V_o = 100 m/s. For each M a set of simulations were carried out for various K values in order to locate the demarcation between bifurcating and non-bifurcating states. Results were obtained by McDonald et al. (1980) for $2 \leq M \leq 30$ (sets of simulations were actually run for M = 2, 5, 10, 30; see fig. 1 where the dots are from the numerical simulation). Values of L_o were obtained from eqn. (7) using V_o = 100 m/s and K = 2 m^2/s.

In the two level numerical simulations of Scannapieco et al. (1976), one level represents the plasma cloud and the other level represents the background ionosphere (two level numerical simulations have also been performed by Lloyd and Haerendel (1973), Scannapieco et al. (1974), and Doles et al. (1976)). This is a simplified model for allowing the plasma cloud to be

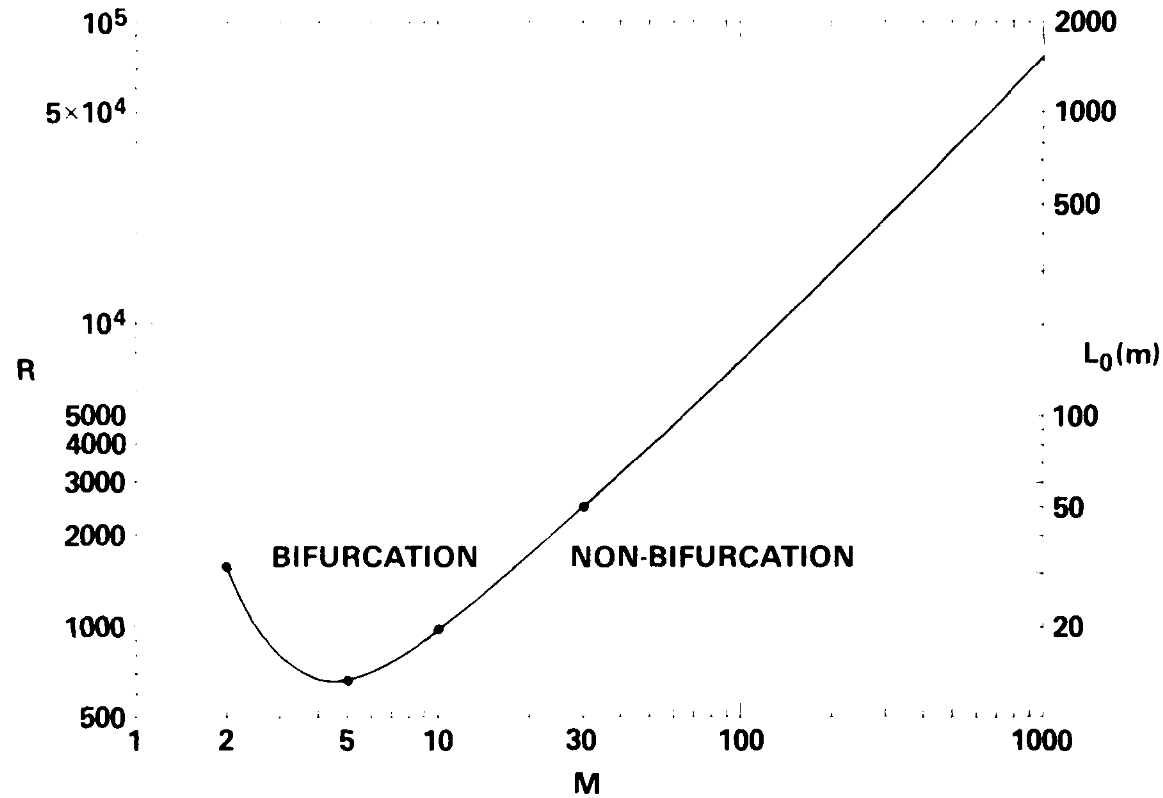

Fig. 1 — Critical R vs M. The solid points are from the simulations of *McDonald et al.* (1980). Similarly, the curve for $2 \leq M \leq 30$ is from this reference. For $M > 30$ the curve has been extrapolated using eqn. (12). L_0 was derived from R by assuming V_0 = 100 m/s and K = 2 m^2/s in eqn. (7).

coupled to a background ionosphere and allowing the ionosphere to react to the cloud. Each of the two levels is characterized by its own zeroth order parameters such as ion-neutral collision frequencies, integrated Pedersen conductivities, etc. The two regions are electrostatically coupled because of the high conductivity along the geomagnetic field. This coupling produces image striations in the background ionosphere (actually below and above the cloud, although the density fluctuations below should be stronger because the plasma compressibility typically decreases with altitude). In this model, ion flow is allowed in each layer, but only the electrons flow (a current) between layers to maintain charge neutrality. Heuristically the two level, two dimensional (x,y) striation model equations were given as

$$\frac{\partial \Sigma^c}{\partial t} = (\ .\ .\ .\ ) \tag{9}$$

$$\frac{\partial \Sigma^i}{\partial t} = (\ .\ .\ .\ ) \tag{10}$$

$$\begin{aligned} &\nabla \cdot (\Sigma \nabla \phi) = (\ .\ .\ .\ ) \\ &\Sigma = \Sigma^c + \Sigma^i \end{aligned} \tag{11}$$

where c and i denote cloud and ionosphere, respectively. In the simulations of Scannapieco et al. (1976) the background ionospheric Pedersen conductivity at $t = 0$ was taken to be uniform and the peak cloud Pedersen conductivity to background ionospheric Pedersen conductivity ratio was taken to be one. The cloud represented a barium cloud released at an altitude of 200 km. As the simulation proceeded image striations were built up in the ionospheric level directly beneath the leading striation fingers at the cloud level. The Pedersen conductivity of these image striations equalled or exceeded the Pedersen conductivity of the cloud striations beneath which they lay. Higher initial Pedersen conductivity ratio clouds tend to produce larger Pedersen conductivity image striations as the cloud evolves (Scannapieco et al., 1974; S. Zalesak, private communication, 1980). Thus, if one looks along a given field line where a high Pedersen conductivity striation (finger) exists, there are also large Pedersen conductivity image striations in the background ionosphere. The net effect of this phenomena is to produce a larger effective Pedersen conductivity ratio on the field line containing the plasma cloud striations and its images (the ratio being measured with respect to the surrounding ionosphere where no image enhancements exist).

II. The Model

Given the introduction in section I of the results of McDonald et al. (1980) and Scannapieco et al. (1976), we now proceed to describe our plausible hypothesis (model) for striation freezing. From the results of McDonald et al. (1980) a "U" shaped curve for $2 \leq M \leq 30$ was produced (see fig. 1). For those numerical simulations the plot suggests that the critical R attains a minimum value between 600 and 700 for $M \simeq 4$. A recent result of Overman and Zabusky (1980) for circular waterbag waterbag clouds supported the qualitative dependence of the critical R upon M as exhibited in fig. 1. They found that shielding and dissipation cooperate to produce an effective diffusivity which is the actual diffusivity times $(M + 1)^2/(M-1)$. If one assumes that the amount of effective diffusivity required to halt bifurcation is insensitive to M, then the critical R should be proportional to $(M + 1)^2/(M-1)$. In fact, McDonald et al. (1980) found that the expression

$$R = 75 \frac{(M + 1)^2}{M - 1} \tag{12}$$

agreed to within 3% of the mean critical R values found in the simulations with the exception of the M = 2 case. In obtaining the L_o presented in fig. 1, McDonald et al. (1980) used $K = 2\ m^2/s$, $V_o = 100$ m/s and used these in eqn. (4).

In fig. 1 to go beyond M = 30 (where McDonald et al. (1980) stopped) we have extrapolated the curve using eqn. (12). Similarly the same values of K and V_o ($2\ m^2/s$ and 100 m/s, respectively) were employed to extrapolate L_o to higher values. From fig. 1 we find that in order to have a minimum scale size $L_o \approx 500$m (which would no longer bifurcate) requires $M \approx 300$. Thus, for barium cloud striations the proposed scenario goes as follows. A nominal Ba^+ cloud might have a Pedersen conductivity ratio (M) $\sim$ 10 (with initial plasma cloud density gradient scale lengths $\sim$ 1-10 km) and fig. 1 shows that this would give a minimum scale size $\sim$ 10-20m, i.e., structure sizes of this order and less would not bifurcate and so would freeze. However, as the plasma cloud steepens and continues to form structures all sizes greater than 10m would be present. During this steepening and structuring process the striation tips (fingers) are forming high Pedersen conductivity (M) regions, including the image striations (as in Scannapieco et al., 1976). As the M value increases with time in these striations the minimal scale size stable against further bifurcation increases. Thus, initially as the plasma cloud structures all scale sizes $\gtrsim$ 10m continue to bifurcate and as time goes on they are sequentially "shut off" (freeze), i.e., the scale size of the marginally stable state increases. The electric field pattern would be determined by the high Pedersen conductivity region (Scannapieco et al., 1974) and so would dominate the bulk motion of the cloud. Thus the cloud would march across the sky at this $\underline{E} \times \underline{B}$ bulk velocity without further bifurcation. In addition, we see from fig. 1 that any structures in very low Pedersen conductivity regions would tend to become stabilized at very large scale sizes (assuming one extrapolates the curve in fig. 1 for M < 2 in a similar fashion).

In the case of nuclear cloud striations, fig. 1 is also illuminating. Late time electrostatic codes such as MELT and MAGIC which take over after the MHD phase (MICE and PHOENIX codes) and follow the evolution of a nuclear detonation into the late time regime ($\gtrsim$ 10 minutes) exhibit large conductivity ratios ($M \sim 10^3$) at the beginning of this phase. Figure 1 would suggest that extremely large R ($\sim 5 \times 10^4$) would delineate the bifurcation from the non-bifurcation state. Moreover, given eqns. (5) - (7), the fact that $V_o \sim 1$ km/s for the nuclear case (in the nuclear case this is the neutral wind velocity), and n is an order of magnitude or so higher for the nuclear case than for the barium cloud case, the L_o in fig. 1 would not be too different for the nuclear situation. This would automatically account for striations ~ 1 km being dominant in the nuclear case in the early phase of the late time regime (structures below this size wouldn't form). Recalling that the studies of McDonald et al. (1980) used no perturbations in the initial condition, a spatially dependent radial neutral wind or strong seed perturbations could result in bifurcation for scale sizes $\lesssim 1$ km in the nuclear case. Of course as the conductivity ratio is reduced for the nuclear cloud bifurcation could occur for smaller and smaller scale sizes without the need for a radially dependent neutral wind. However, as the late time regime proceeds the nuclear cloud will become more barium cloud-like in nature.

III. Conclusions

A plausible hypothesis for striation freezing in ionospheric plasma clouds, extrapolating from the works of McDonald et al. (1980) and Scannapieco et al. (1976), has been presented. The second level (background ionosphere) effect of amplifying the integrated Pedersen conductivity in a striation (image striations), because the second level is compressible, could result in larger minimum striation scale sizes, as time goes on, which would no longer bifurcate (but would freeze). Extrapolating McDonald et al's. (1980) "U" shaped curve (see fig. 1) to higher integrated Pedersen conductivity ratios (M) yields, for example, $L_o \sim 500m$ for $M \sim 300$. This could account for the persistence (i.e., freezing) of km scale-size structures observed in late time barium cloud evolution, as the striations drift in unison. The hypothesis warrants more detailed two level numerical simulations, including electron-ion collision effects and going to longer times. In addition, one should look for image striation effects in the observations (note: Preliminary evaluation of the in situ mass spectrometer and plasma density probe measurements taken during the DNA PLACES barium cloud experiment show image striations, R. Narcisi and E. Szuszczewicz, private communication, 1981).

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